NASA TECHNICAL NOTE

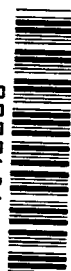# EXPERIMENTAL VERIFICATION OF AN ANALYTICAL DETERMINATION OF OVERALL THERMAL CONDUCTIVITY OF HONEYCOMB-CORE PANELS

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DETERMINATION OF OVERALL THERMAL CONDUCTIVITY OF

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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SUMMARY

The overall thermal conductivity of four honeycomb-core panels was determined over a temperature range from 1200° R (670° K) to 1900° R (1050° K). The brazed panels were fabricated from a cobalt-base alloy. The ratio of height to cell width of the honeycomb core in the panels varied from 1 to 5. Thermal conductivities were determined in an insulated apparatus which utilized a steady-state heat flow through the panels.

In order to verify an analytical determination of the overall thermal conductivity of honeycomb-core panels, the results of the present investigation were compared with the results calculated from an analysis reported in NASA TN D-714. There was a root-mean-square deviation of 7 percent between analytical and experimental results.

INTRODUCTION

In the analytical determination of overall thermal conductivity of honeycomb-core panels given in reference 1, the comparison made between the results calculated by this analysis and the experimental results available at that time was in a temperature region where radiation was not significant. In the present paper, an experimental study was made to verify the analysis at higher temperatures where radiation is the dominant mode of heat transfer. Four panels fabricated from a cobalt-base alloy were used in the investigation, which covered a temperature range from approximately 1200° R (670° K) to 1900° R (1050° K). The ratio of height to cell width of the honeycomb core in the panels varied from 1 to 5. This range of core height to cell width should cover most honeycomb-core panels encountered in practical applications.

SYMBOLS

The units used for the physical quantities defined in this paper are given both in the U.S. Customary Units and in the International System of Units (SI). Factors relating the two systems are given in reference 2.

A   area, ft^2 (m^2)

ΔA cross-sectional area of conduction path through core material, ft^2 (m^2)

$\Delta A/A$ solidity of core

d   equivalent cell diameter, ft (m)

k   thermal conductivity, Btu/ft-hr-$^{\circ}$R (W/m-$^{\circ}$K)

l core height, ft (m)

q   rate of heat transfer per unit area, Btu/ft^2-hr (W/m^2)

T   temperature, $^{\circ}$R ($^{\circ}$K)

ϵ emissivity

λ ratio of core height to cell diameter, l/d

σ Stefan-Boltzmann constant, 0.476×10^{-12} Btu/ft^2-sec-$^{\circ}$R^4 $(56.7 \ nW/m^2$-$^{\circ}$K$^4)$

Subscripts:

a   air

av   average

C   cold face

calc   calculated

H   hot face

meas   measured

m   metal

o   overall

r   radiation

APPARATUS AND PROCEDURE

Test Panels

Four hexagonal-honeycomb-core panels fabricated from a cobalt-base alloy (AMS 5537) were used in the experimental study to determine thermal conductivity. The test panels were 2 feet by 2 feet (0.61 m by 0.61 m) and varied in thickness from 0.296 inch to 1.400 inches (0.75 cm to 3.56 cm). The thickness variation corresponds to a variation from 1 to 5 in the ratio of height to effective width of the honeycomb cell. Dimensions of the panels are shown in figure 1.
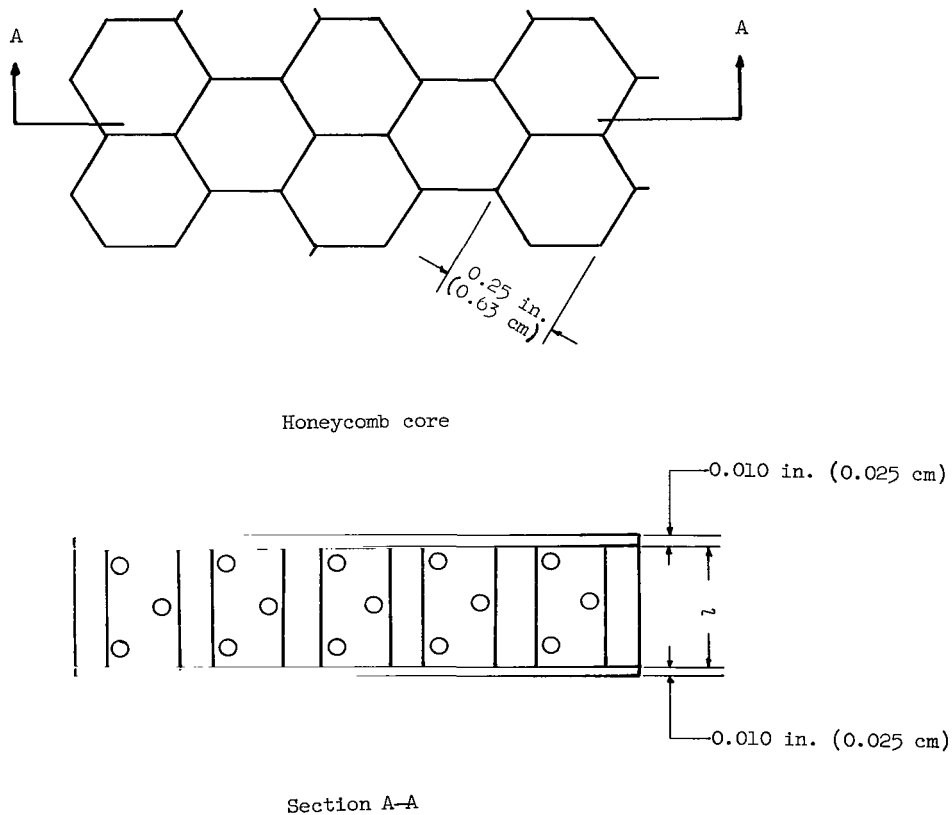

Honeycomb core

Section A-A

Core dimensions				
λ	1	2	3	5
l,in.	0.276	0.552	0.838	1.38
l,cm	0.701	1.40	2.10	3.51

Figure 1.- Details of honeycomb-core panel.

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The core material was 0.002-inch (0.05-mm) foil and each cell was vented so that it could be evacuated. The face sheets were brazed to the core, and X-rays were made to determine whether each cell was brazed to the sheets. Examination of the X-rays showed only one cell which was not properly brazed, and this cell was outside the area in which measurements were made.

The four panels were instrumented with nine chromel-alumel thermocouples on each face in a pattern shown in figure 2. The two wires of each thermocouple were welded to the surface of the panel as close together as possible without touching. Each thermocouple junction was located in the center of a honeycomb cell. The insulation was removed from the section of the duplex thermocouple wire which extended across and over the edge of the panel; this portion of the insulation was replaced by alumina tubing. The remaining duplex wire was used as leads.
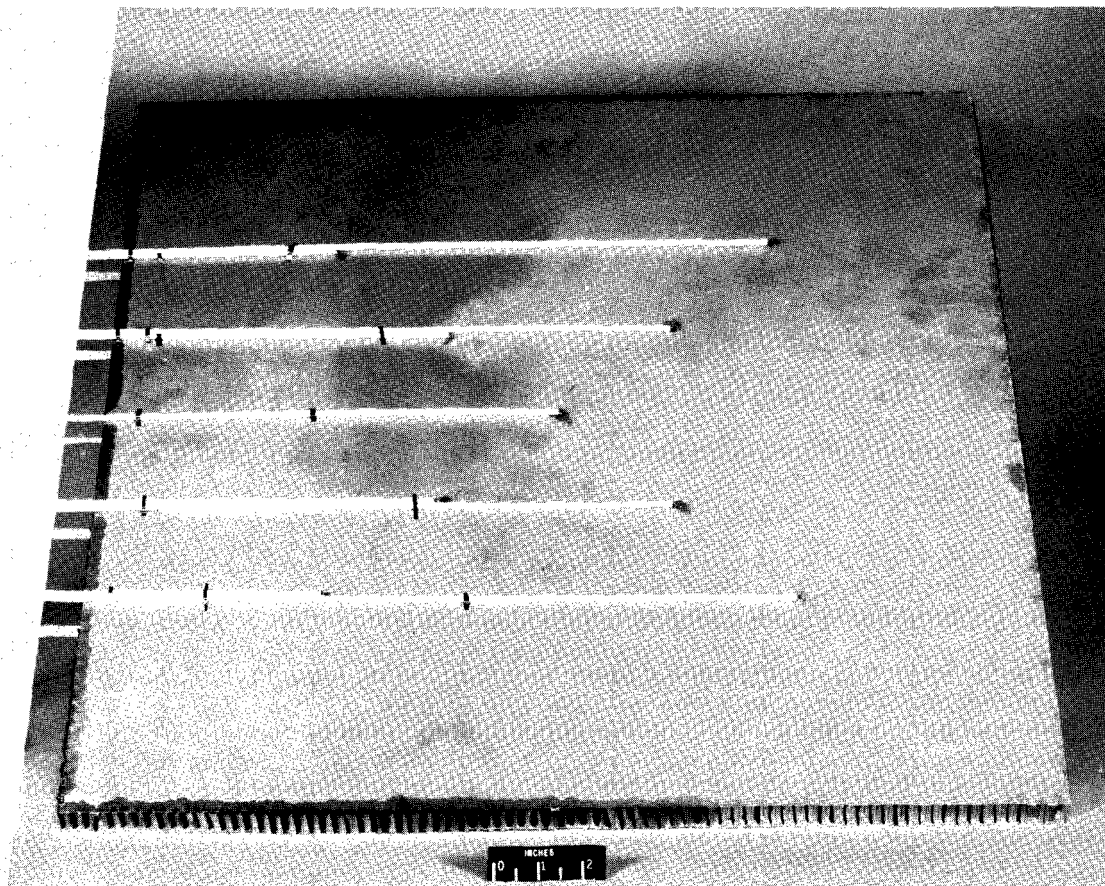

Figure 2.- Honeycomb-core sandwich panel with thermocouples attached.   L-63-2938

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The experimental determinations of thermal conductivity were made in an apparatus designed for panels up to 2 feet by 2 feet by $4\frac{1}{2}$ inches (0.61 m by 0.61 m by 11.4 cm). Basically this apparatus consists of a series arrangement of a heater assembly and a heat-rate transducer with sufficient space between heater and transducer for insertion of test panels and insulation. Only the center square foot (0.093 m^2) of the panel is used in obtaining the data so that the remainder of the panel provides a natural guard area which reduces error caused by lateral conduction. Figure 3 shows the apparatus with the movable vacuum chamber rolled back to expose the test area. The test area is shown in more detail in figure 4. The molybdenum disilicide heating elements terminate in a water-cooled aluminum cap through which power is applied to these elements. The heating circuit is electrically isolated from the cooling circuit by nylon bushings which provide continuity for the water flow. The aluminum oxide plate, which supports the heating elements, is supported around the perimeter by blocks of foamed silica. The transducer is bonded to the water-cooled plate with a cement of high thermal conductivity. The insulation which separates the transducer from the test panel was chosen so that its thermal conductivity was similar to that of the transducer. The insulation has the twofold purpose of raising the average temperature of the panel and preventing the transducer from overheating.
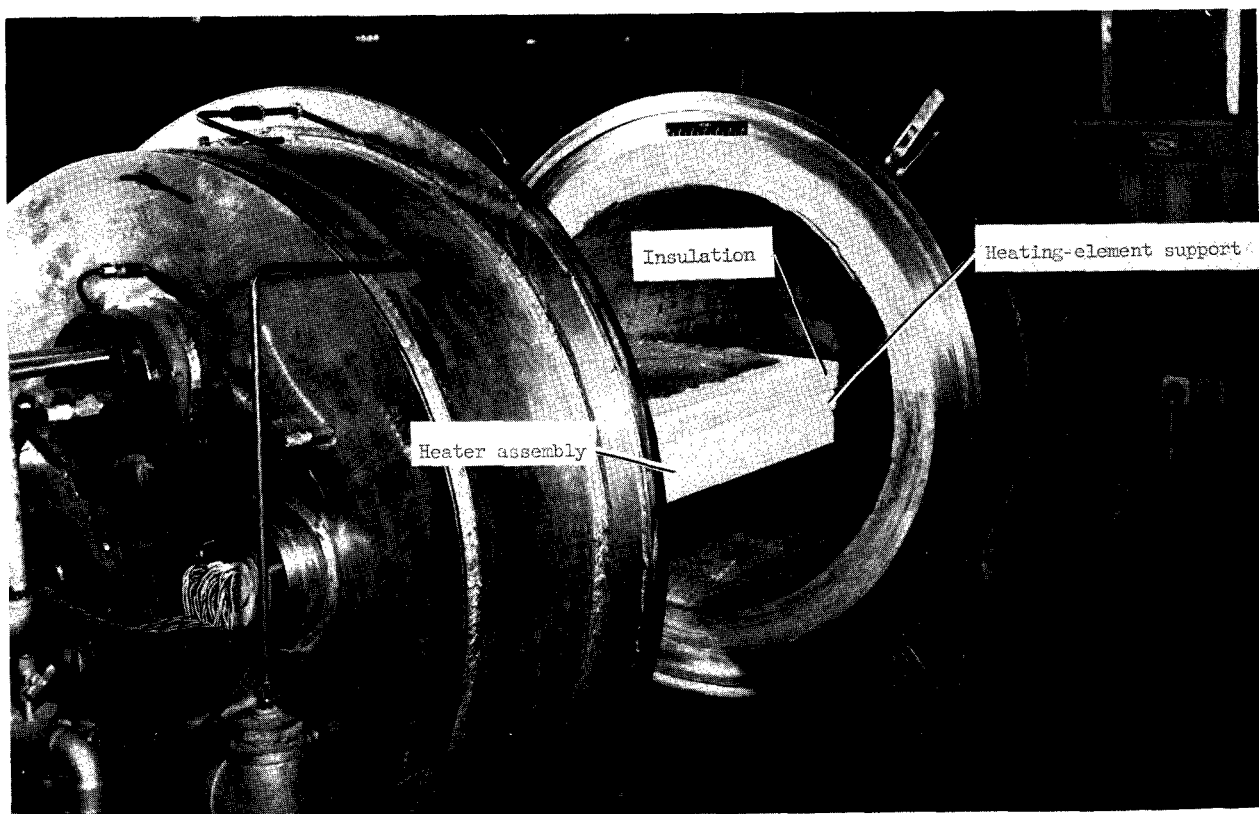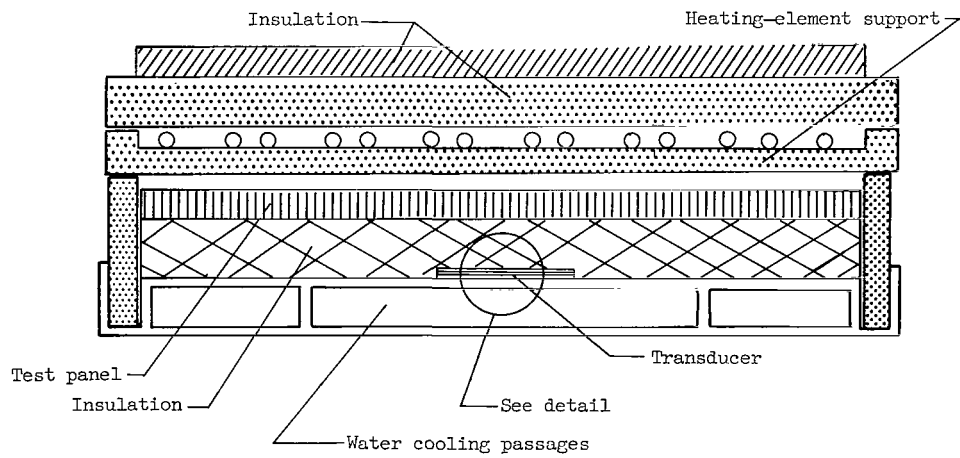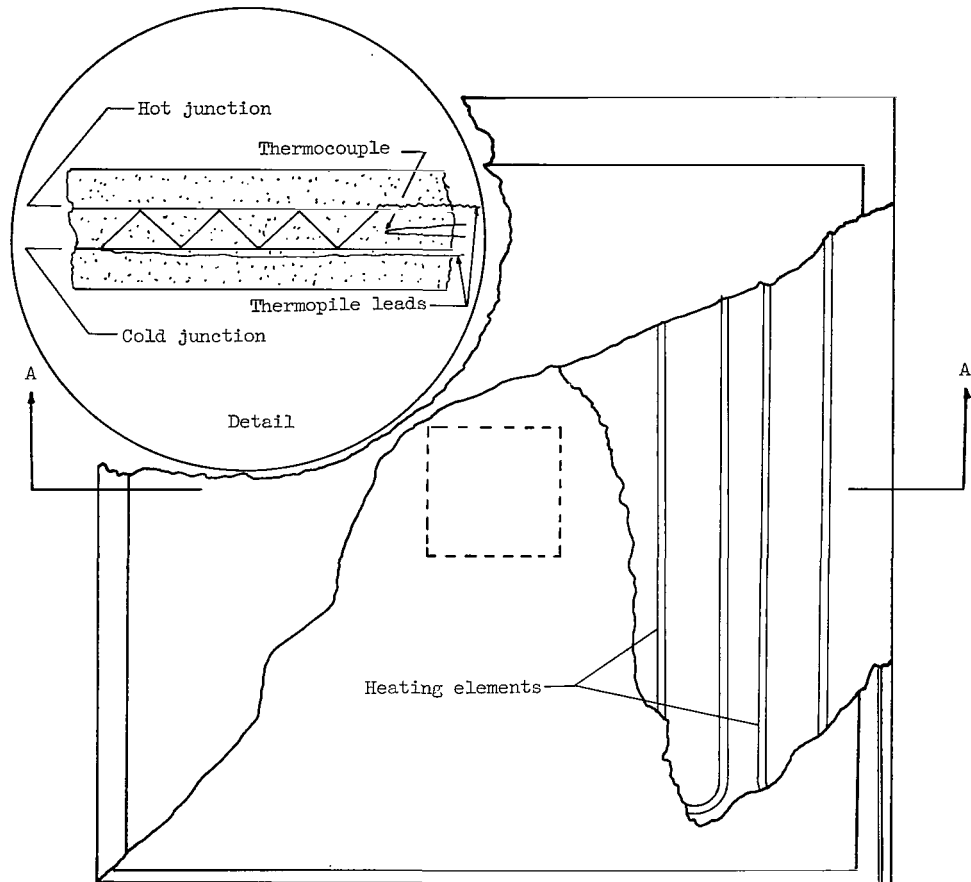

Figure 3.- Thermal-conductivity apparatus with chamber in open position.   L-63-6955.1

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Hot junction

Thermocouple

Thermopile leads

Cold junction

Detail

A

A

Heating elements

Insulation

Heating-element support

Test panel

Insulation

Water cooling passages

Transducer

See detail

Section A–A

Figure 4.- Details of test area.

The transducer, which produces an electromotive force proportional to the heat-flow rate, is composed of a silver-constantan thermopile. This thermopile is arranged in a thin phenolic resin plate sandwiched between two other phenolic resin plates as shown in figure 4. The series of thermocouples making up the thermopile is positioned so that one set of junctions is on one face of the middle plate and the other set of junctions is on the other face of the middle plate. Heat flow causes a difference in temperature across the plate and thus generates an electromotive force. The calibration curve which relates electromotive force and heat-flow rate was determined by the manufacturer from tests performed in a guarded hot plate conforming to standards of the American Society of Testing Materials. This curve is a function of the average transducer temperature that was measured with the thermocouple in the middle plane of the transducer.

All data were recorded continuously by using the Langley central digital data recording facility. In addition, transducer output and significant temperatures were monitored at the apparatus site.

Test Procedure

After a honeycomb-core panel was placed in the test chamber, the apparatus was run at elevated temperature and atmospheric pressure so that an oxidized surface of constant emissivity was obtained. This procedure prevented variations in emissivity caused by increasing oxidation as the mean temperature increased from approximately 1200° R (670° K) to 1900° R (1050° K) during successive runs. A series of tests at different temperatures was then made on the oxidized panel.

The same general procedure was followed for all tests. The vacuum chamber was sealed and evacuated to a pressure of 500 microns of mercury (67 N/m^2). The temperature controller was set to a level which would give a temperature-rise rate not exceeding 20° R per minute (0.185° K per sec). As soon as the desired temperature was reached, the temperature controller was adjusted so that a constant temperature was obtained by varying the amount of current flowing through the heating elements. After several hours, the heat-flow rate through the panel reached a steady-state condition. When the instruments indicated that this condition had been reached, the local monitors were switched out of the circuit and the data were recorded.

The calibration of the transducer was checked after all the panels had been tested to make certain that no calibration changes caused by thermal or mechanical damage to the transducer had occurred during the tests. High-purity iron slab of known chemical composition was used as a standard. Values of thermal conductivity as a function of temperature were taken from reference 3 for high-purity iron with a similar chemical composition. Values of the thermal conductivity determined by the transducer differed by a maximum of 5 percent from values of the thermal conductivity reported in reference 3. Inasmuch as this difference was well within the range of experimental error, the calibration was assumed to have been unchanged.

EQUATIONS USED TO CALCULATE OVERALL THERMAL CONDUCTIVITY

The calculated values of overall thermal conductivity were determined from the equations given in reference 1 which include the effects of conduction through the cell walls as well as radiation and conduction through the air contained in the honeycomb cells. The equations, given in the notation of the present paper, are as follows: The equations of heat transfer by the different modes are given as

$$q_m = \frac{k_m}{l}\left(\frac{\Delta A}{A}\right)\left[\left(T_H\right)_{av} - \left(T_C\right)_{av}\right] \tag{1}$$

$$q_r = 0.664(\lambda + 0.3)^{-0.69}\epsilon^{1.63(\lambda+1)^{-0.89}}\sigma\left\{\left[\left(T_H\right)_{av}\right]^4 - \left[\left(T_C\right)_{av}\right]^4\right\} \tag{2}$$

$$q_a = \frac{k_a\left[\left(T_H\right)_{av} - \left(T_C\right)_{av}\right]}{l}\left(1 - \frac{\Delta A}{A}\right) \tag{3}$$

The overall thermal conductivity is then defined as

$$k_o = \frac{\left(q_a + q_m + q_r\right)l}{\left(T_H\right)_{av} - \left(T_C\right)_{av}} \tag{4}$$

Inasmuch as the analysis utilized a cylindrical rather than a hexagonal cell for the honeycomb core, an adjustment was made to adapt the analysis to the panels of the present investigation: The diameter of the cylinder was adjusted so that the perimeters of the two cells were equal. The diameter of the cylinder which corresponded to each respective hexagon was used to determine the value of l/d or λ.

COMPARISON OF ANALYTICAL AND EXPERIMENTAL RESULTS

Values of the overall thermal conductivities determined from both the experiment and the analysis are plotted as a function of panel temperature in figure 5. The comparisons shown are for the four test panels having values of λ equal to 1, 2, 3, and 5. The mean temperatures ranged from approximately 1200° R (670° K) to 1900° R (1050° K). The solid line represents the thermal conductivity calculated by the analysis in reference 1. The calculated values utilized thermal-conductivity data for AMS 5537 which are given as a function of temperature in reference 4. An emissivity value of 0.89 was used in the calculations, and the panel temperatures that were used are presented in table I.
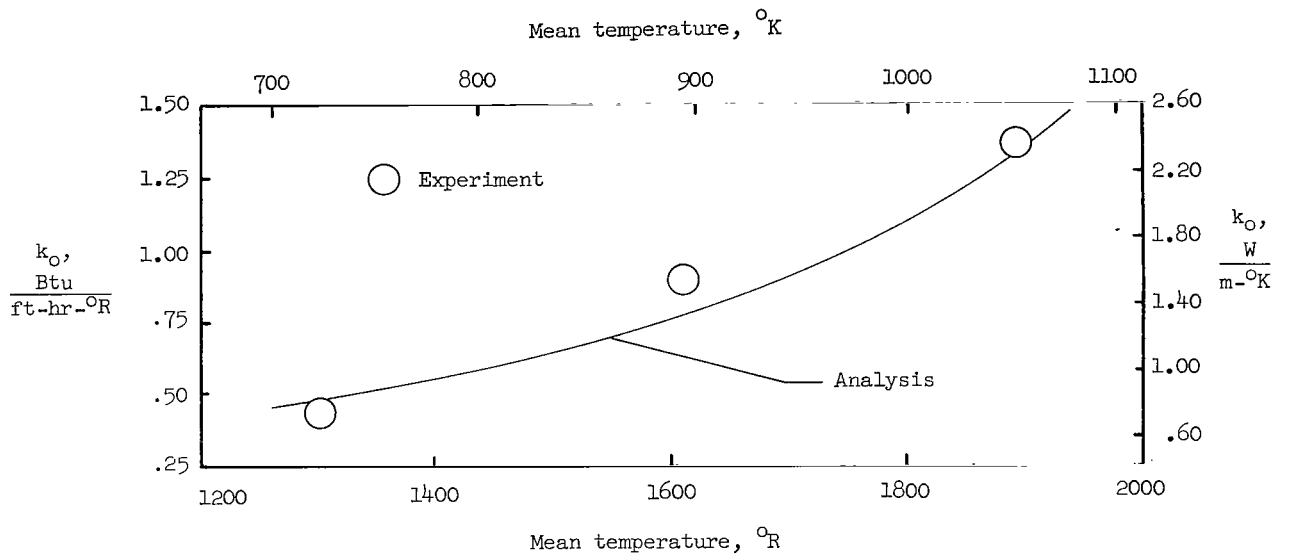
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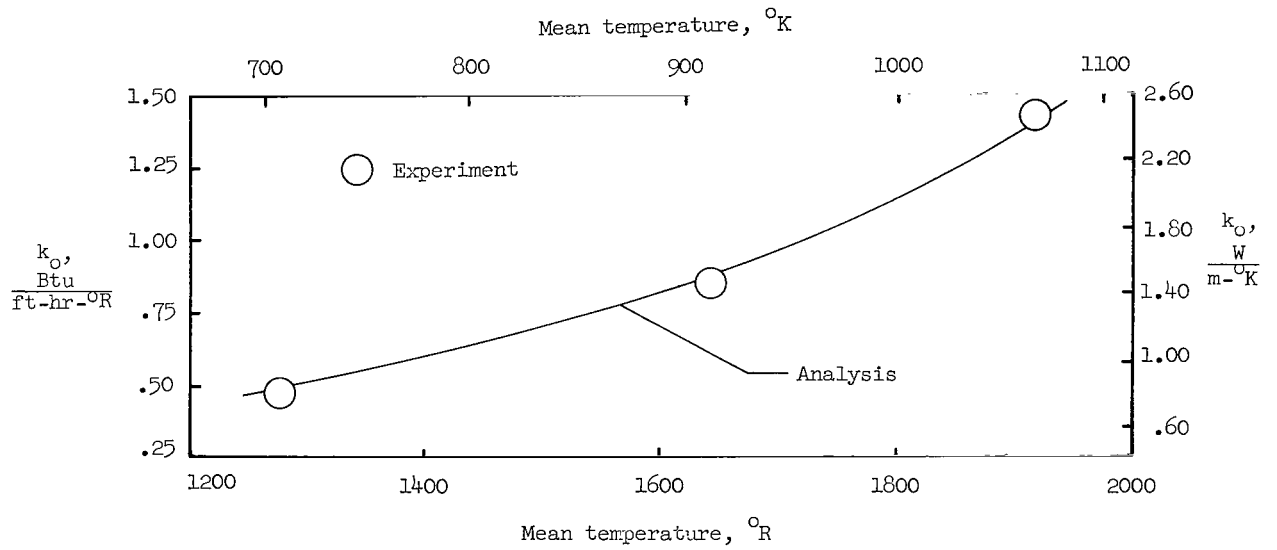Mean temperature, $^\circ$K

(a) $\lambda = 1$.
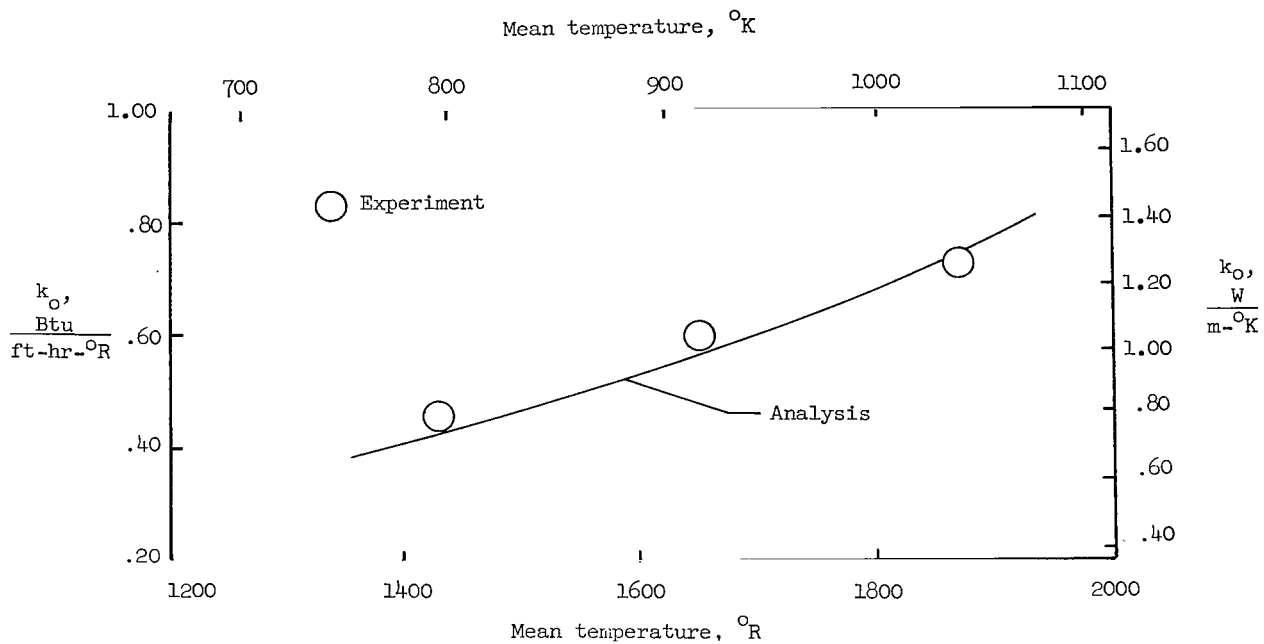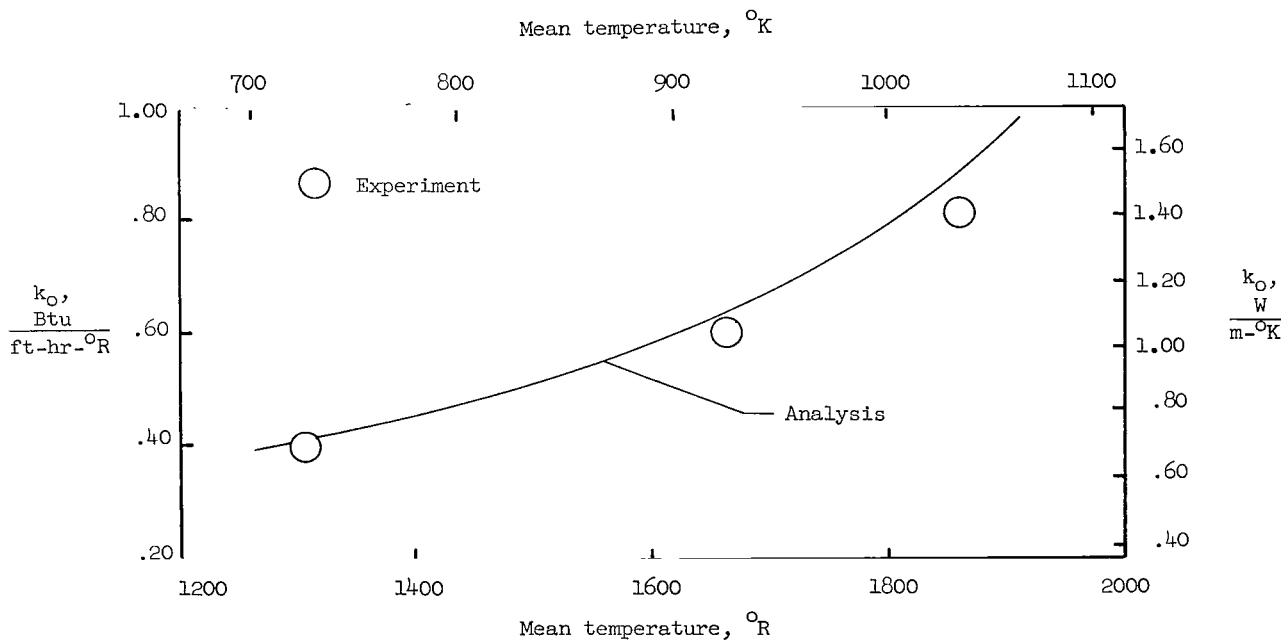
Mean temperature, $^\circ$K

(b) $\lambda = 2$.

Figure 5.- Comparison of experimental and analytical results of overall thermal conductivity for four values of λ.

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(c) λ = 3.

(d) λ = 5.

Figure 5.- Concluded.

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TABLE I

PANEL TEMPERATURES

$(T_H)_{av}$		$(T_C)_{av}$		Maximum deviation from average temperature		$(T_H)_{av} - (T_C)_{av}$	
°R	°K	°R	°K	°R	°K	°R	°K
$\lambda = 1$							
1428	793	1419	788	2	1.1	9	5
1651	917	1640	911	3	1.6	11	6
1868	1038	1855	1030	1	.5	13	7
$\lambda = 2$							
1305	725	1288	715	1	0.5	17	9
1661	923	1638	910	4	2.2	23	13
1858	1032	1834	1019	3	1.6	24	13
$\lambda = 3$							
1303	724	1270	705	4	2.2	33	18
1611	895	1591	884	3	1.6	20	11
1890	1050	1869	1038	3	1.6	21	12
$\lambda = 5$							
1279	710	1245	692	2	1.1	34	19
1640	911	1603	890	3	1.6	37	20
1914	1063	1879	1044	2	1.1	35	19

The results are shown in a condensed form in figure 6 in which the ratio of the measured overall conductivity to the calculated overall conductivity is shown for the various values of λ. Agreement between experimental and analytical results is within 16 percent over this wide range of λ, with a root-mean-square deviation of 7 percent. The temperatures involved are high enough to insure that radiation is the predominant mode of heat transfer at 1900° R (1050° K); that is, the amount of heat transferred through the honeycomb-core panel by the radiation mode is 70 to 80 percent of the total heat transferred. Therefore, the analysis should be valid for higher temperatures than those encountered in these tests.
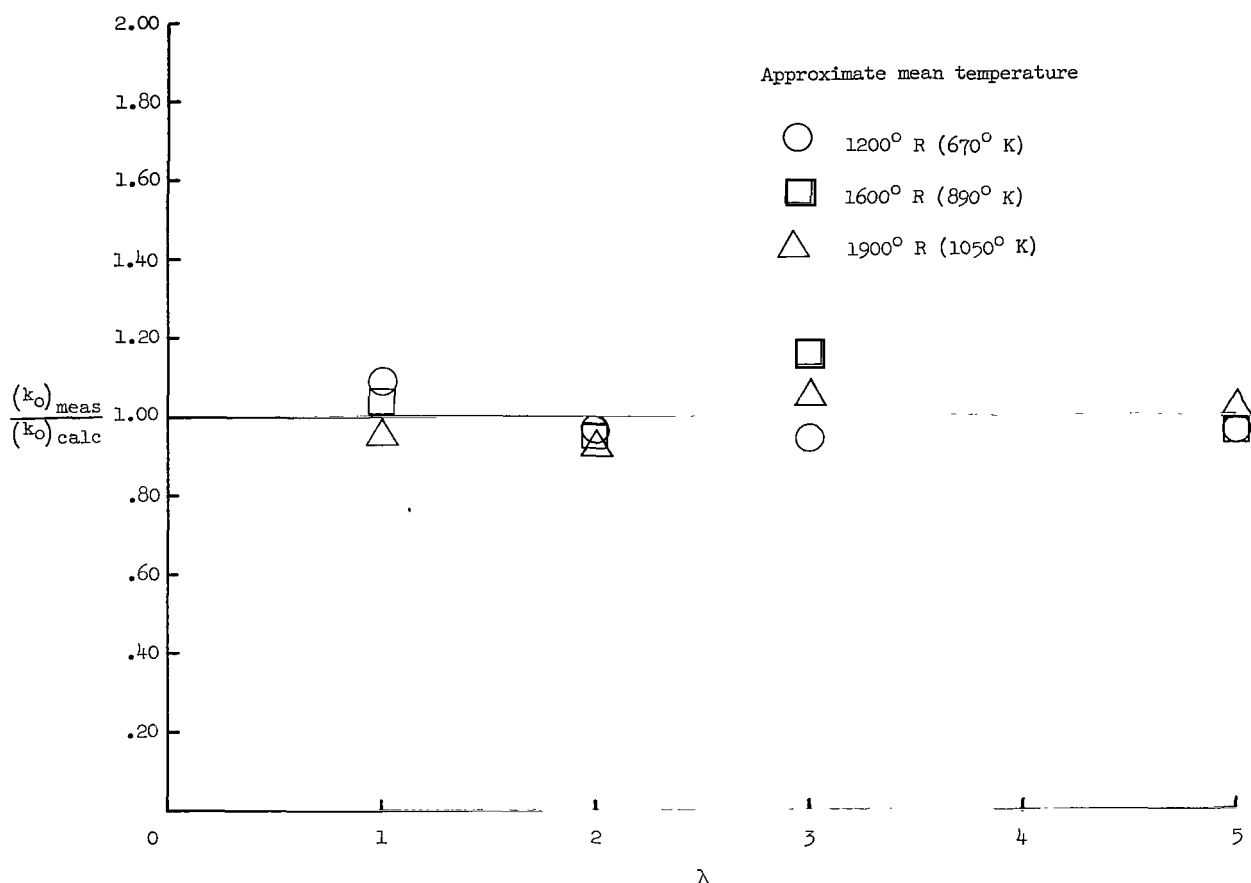
Figure 6.- Ratio of measured to calculated overall thermal conductivity for four values of λ.

CONCLUDING REMARKS

Thermal conductivities were determined from tests of four honeycomb-core panels in a special insulated apparatus over a temperature range from 1200° R (670° K) to 1900° R (1050° K). The ratio of height to cell width of the honeycomb core in these panels varied from 1 to 5. This range covers most honeycomb-core panels encountered in practical applications. The results of this investigation showed that an existing analysis predicts the overall conductivity of such panels with a root-mean-square deviation of 7 percent. Since the highest test temperature was in a region where radiation is the predominant mode of heat transfer, use of the analysis for higher temperatures than those encountered in the present investigation is considered justified.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., March 10, 1965.

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—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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